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Criterion of Crack Resistance of Corrosion Damaged Concrete in Plane Stress State

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Abstract

A criterion of crack resistance corrosion damaged concrete in plane stress state with colmatation transformation of the concrete structure is built in the coordinate system of the principal normal stresses. Criterion of crack resistance is described by the elliptic curve typical dimensions of which are determined by the kinetics parameters of corrosion damage progress in time and by depth of damages, level and sign of the stress state. This criterion allows taking into account changes in the structure of concrete at various kinds of stress state (tension - tension, compression - compression and tension - compression) with respect to the characteristic types of possible cracks in plane stressed elements. The resulting criterion is quite general and can be used not only for the evaluation of crack resistance for plane stressed concrete and reinforced concrete elements, as well as for solving problems of exposure of residual resource and survivability of exploited reinforced concrete structures under the simultaneous display of force and environmental impacts over time.

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Keywords: Stress state, criterion of crack resistance, corrosion damaged concrete, kinetics of damage, corrosion depth.

1. Introduction

Studies carried out in the last decade, for example, [1–3, 9–18] found that the intensity of the corrosion damages of exploited reinforced concrete structures is determined not only by the degree of aggressiveness of the environment, but also by the type and level of stress state in the structural elements. In this regard, the formulation

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and solution for the problem of the dynamics of crack resistance changes in time for complex stressed reinforced concrete structures, for example, areas of joint action of bending moments and shear forces in the beam structure, is of current interest. [19–21] (Fig. 1). The results of studies of these areas so far remain a topic of discussion on the differences of approaches to solving problems of crack resistance, strength and deformability of the force resistance of these zones.

Moreover, formulated new research direction in the study of exploited reinforced concrete structures to assess their survivability [4] is related to the need to quantify the crack resistance and strength of the cross section, during the simultaneous display of force and environmental impacts.

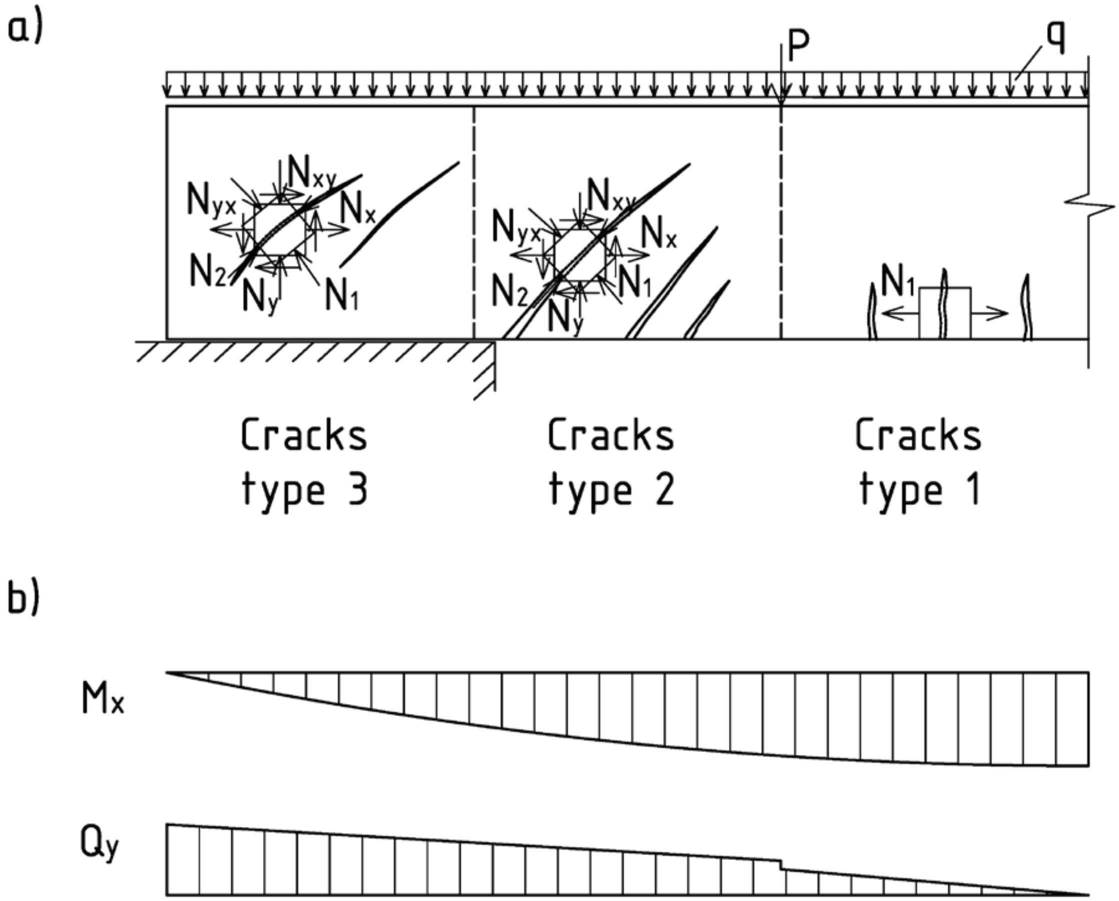

Fig. 1. Typical stress states, crack types in plane stressed reinforced concrete elements (a) and bending moment and shear forces on the considered part of the beam (b)

2. Formulation of the crack resistance criterion for the loaded corrosion damaged element

For the general case of a triaxial stress state crack resistance criterion for corrosion damaged concrete in the system of main forces (N1, N2) applied at the middle surface of the characteristic small element of unit dimensions can be represented in the form:

$$N_1^2 + N_2^2 + N_3^2 - \frac{1}{2} N_1 \cdot N_2 \cdot N_3 - (R_b^*(t) \cdot b - R_{bt}^*(t) \cdot b) \cdot (N_1 + N_2 + N_3) - R_b^*(t) \cdot R_{bt}^*(t) \cdot b^2 = 0. \quad (1)$$

Under the plane stress state (N3 = 0) the crack resistance of the corrosion damager concrete can be determined by the elliptic curve:

$$N_1^2 + N_2^2 - \frac{1}{2}N_1 \cdot N_2 - (R_b^*(t) \cdot b - R_{bt}^*(t) \cdot b) \cdot (N_1 + N_2) - R_b^*(t) \cdot R_{bt}^*(t) \cdot b^2 = 0, \quad (2)$$

where Rb*(t), Rbt*(t) – ultimate strength of corrosion damaged concrete under uniaxial compression and uniaxial tension, respectively, b – the width of the considered beam.

Studies [1,5] determined that development of corrosion damage in time and depth of aggressive environment neutralization are various and depend on the level of stress state (N/R*b), of concrete composition and characteristics of physical and chemical impacts. In this case, there are three variants of development of the degrading changes in the cross section structure of reinforced concrete element:

1. Entropy, fading over time, due to the reduction of permeability owing to compaction and colmatation transformation of concrete structure, with the gradual stabilization on some critical (or limiting) the depth of damage δcr;
2. Linear, with a constant speed, front advancement of corrosion, without its stabilization at a certain depth; Here the value δcr changes the original meaning and becomes a kind of empirical parameter of the process of damage;
3. Avalanche, intensifying over time, corrosion damage leads to the complete destruction of the material.

Later in assessing the crack resistance of plane stressed elements the first version of corrosion damage with colmatation transformation of concrete structure and stabilization of damage at a certain depth δcr will be considered.

Following the dependences shown in [5,6] and graphically depicted in figure (Fig. 2) it can be seen that changes in the strength characteristics of reinforced concrete elements and therefore the current values of the depth of damage δcr under corrosion damage are determined over time by the speed and type of injury (empirical kinetics parameters of damage α, m) as a function of the level and sign of the stress state. For the considered colmatation type of damage the maximum depth of damage fore concrete under compression at some point of the current time following [5] can be determined from the expression:

$$\Delta\delta(t, t_0) = \frac{\delta_{cr} - \delta(t, t_0)}{\delta(t_0)} \quad (3)$$

where t – current time, t0 – start time of observation.

For numerical calculations parameters δcr, α, m can be presented analytically in the form of some polynomials of the type:

$$\delta_{cr}\left(\frac{N_c}{R_b}\right) = \sum_{i=0}^{i=3} q_{\delta i}\left(\frac{N_c}{R_b}\right)^i; \quad \frac{\partial \delta_{cr}\left(\frac{N_c}{R_b}\right)}{\partial\left(\frac{N_c}{R_b}\right)} = \sum_{i=1}^{i=3} i q_{\delta i}\left(\frac{N_c}{R_b}\right)^{i-1};$$

$$m\left(\frac{N_c}{R_b}\right) = \sum_{i=0}^{i=3} q_{mi}\left(\frac{N_c}{R_b}\right)^i; \quad \frac{\partial m\left(\frac{N_c}{R_b}\right)}{\partial\left(\frac{N_c}{R_b}\right)} = \sum_{i=1}^{i=3} i q_{mi}\left(\frac{N_c}{R_b}\right)^{i-1}; \quad (4)$$

$$\alpha\left(\frac{N_c}{R_b}\right) = \sum_{i=0}^{i=3} q_{\alpha i}\left(\frac{N_c}{R_b}\right)^i; \quad \frac{\partial \alpha\left(\frac{N_c}{R_b}\right)}{\partial\left(\frac{N_c}{R_b}\right)} = \sum_{i=1}^{i=3} i q_{\alpha i}\left(\frac{N_c}{R_b}\right)^{i-1}.$$

For each type of concrete, speed and type damage fixed parameters δcr, α, m are determined experimentally and with their help qδi, qmi, qαi are calculated.

Similar dependences for determining the empirical parameters δkp, α, m can be recorded also for biaxial stretching using data from [6].

We consider the case for the plane stress state - compression in one direction and tension in another direction. Empirical parameters of the kinetics of damage in the first approximation can be calculated using dependencies [5] described for the stress state of compression - compression (Fig. 2b) by formulas (Eq. 3) and (Eq. 4) of dependencies from work [6] for the stress state of tension - tension (Fig. 2a).

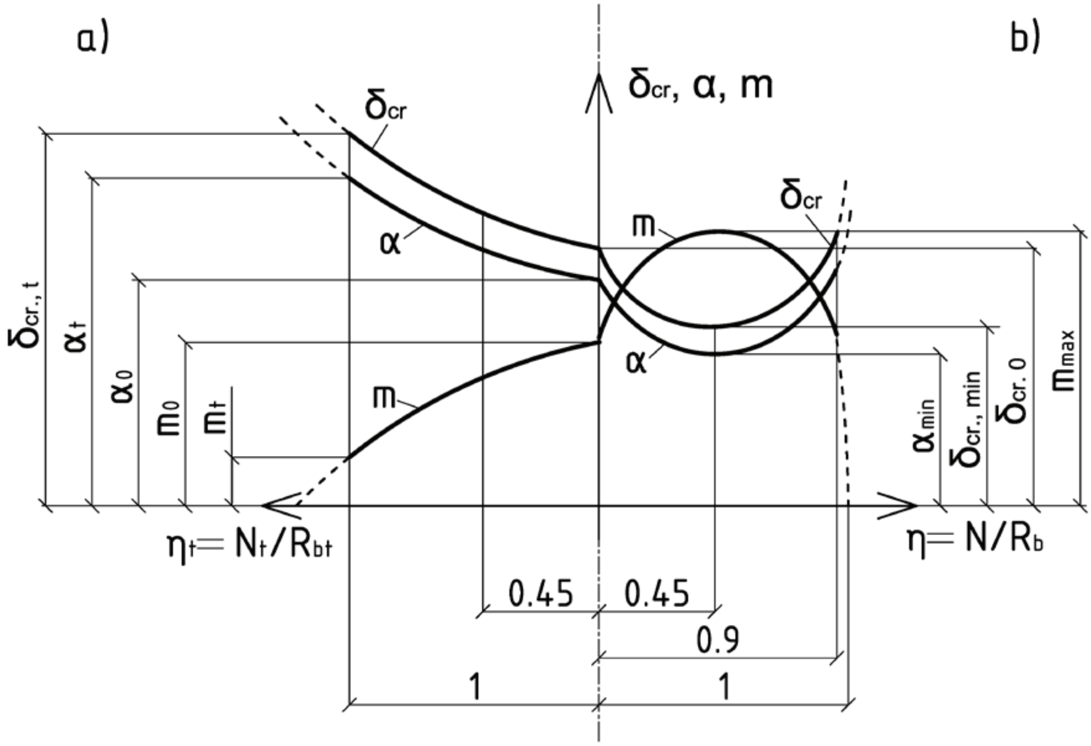

Fig. 2. Scheme parameter changes for δcr, α, m in a – biaxial tension and b – biaxial compression depending on level of stress state η

Using these dependencies the crack resistance criterion for plane stressed element in the development of the kinetics of damage in time for the two types of possible cracks (crack type 1 and type 2) can be defined. The data from works [7,8] in which the influence of the joint action of the load and corrosion damage is given to a 2% aqueous solution of sulphuric acid is used for finding the empirical parameters of the kinetics of damage.

Graphs of strength criterion for plane stress state tension - compression built for the following cases of stress state are considered:

a) at N1 = 0:

$$N_2 = \frac{(R_b - R_{bt})}{2} - \sqrt{\frac{(R_b - R_{bt})}{4} + R_b R_{bt}}\,, \tag{5}$$

$$N_2{}^2 - (R_b - R_{bt})N_2 - R_b R_{bt} = 0, \tag{6}$$

$$N_2{}^1 = R_b, \qquad N_2{}^2 = -R_{bt}, \tag{7}$$

which corresponds to points B and B’ at the graph (Fig. 3).

b) at N1 = N2 = p – uniform biaxial compression and tension:

$$p = \frac{2}{3}(R_b - R_{bt}) \pm \sqrt{\frac{4(R_b - R_{bt})^2}{9} + \frac{2}{3} R_b R_{bt}}. \quad (8)$$

The values p(1) and p(2) corresponds to the points A and A' (Fig. 3).

c) at N1 = -N2 = f – case of pure shear

$$f = \sqrt{\frac{R_b R_{bt}}{2,5}}, \quad (9)$$

which corresponds to point C.

d) extreme value of N_1, following from the condition $dN_1 / dN_2 = 0$, correspond to the values:

$$N_2 = \frac{N_1}{4} + \frac{(R_b - R_{bt})}{2}, \quad (10)$$

$$N_{1\,\substack{max\\min}} = \frac{2}{3}(R_b - R_{bt}) \pm 4\sqrt{\frac{2(R_b - R_{bt})^2}{45} + \frac{1}{15} R_b R_{bt}} \quad (11)$$

Using the values of obtained characteristic points of the crack resistance criterion of corrosion damaged cross section of plane stressed concrete element are built for two characteristic stress states (Fig. 2): at η = 0 and at η = 0.3 and two equations of the current values of the damage depth t0= 0 (re-produced structureand exploited in an aggressive environment structure after t = 150 days. (Fig. 3)

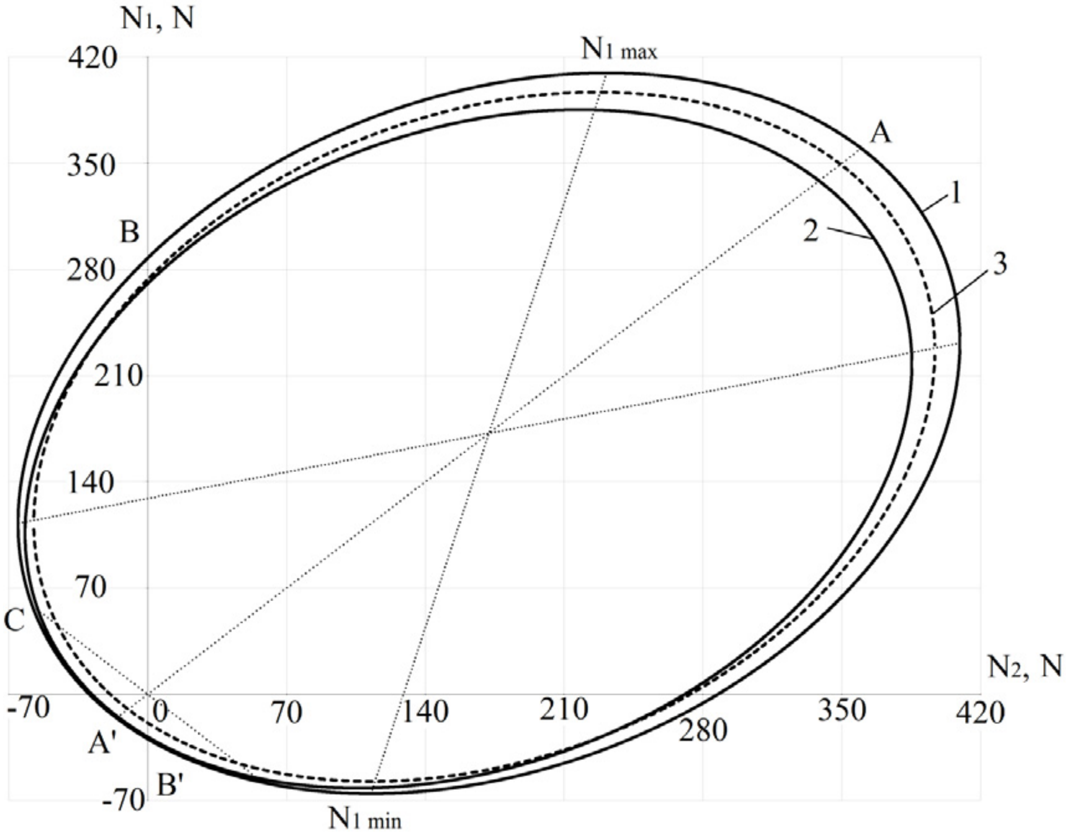

Fig. 3. Graphs for the crack resistance criterion of corrosion damaged concrete at plane stress state: 1 – for undamaged concrete (t = 0); 2 – for corrosion damaged concrete excluding changes in the structure concrete during loading; 3 – for corrosion damaged concrete considering changes in the structure of concrete during loading

Fragments of crack resistance for corrosion damage and loaded element for cracks first and second type (Fig. 4) were drawn: curve 1 is for loaded and undamaged by corrosion element, curve 2 is for corroded element at the current time t = 150 days.

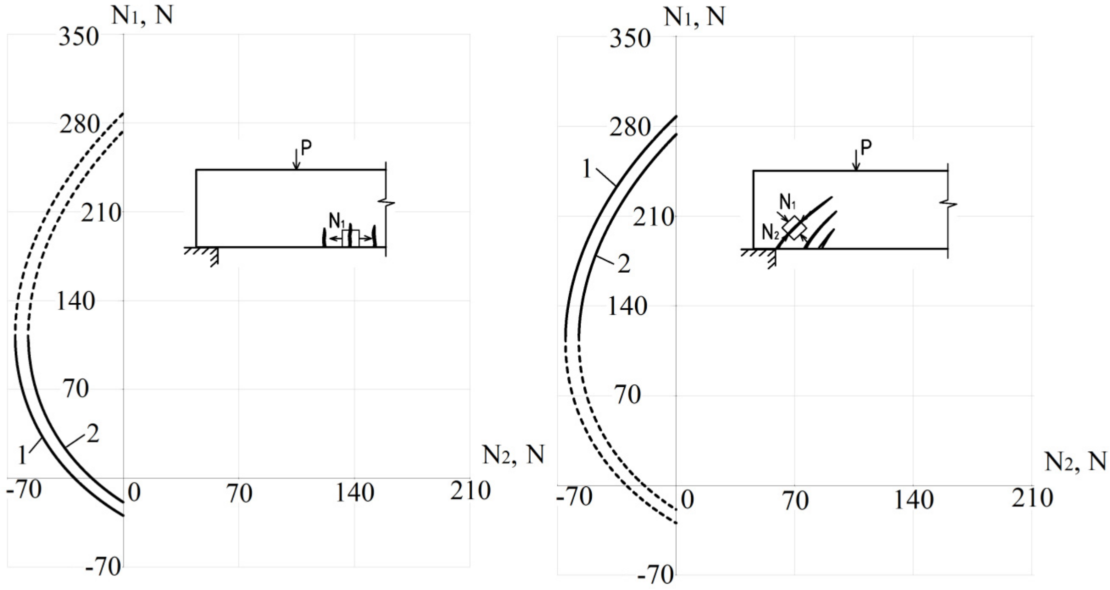

Fig. 4. Crack resistance criterion for the plane stressed concrete element under stress state compression - tension before the formation of the characteristic cracks of first and second types excluding 1 and considering 2 corrosion damages

3. Conclusions

From the above analysis it follows that the ultimate resource of crack resistance for loaded and corrosion damaged concrete element is defined by the equation and the sign of the stress state, the parameters of the kinetics progress of damage over time (δcr, α, m). The resulting criterion is quite general and can be used not only to assess all types of cracks in plane stressed elements, but also for the analysis of survivability exposure of reinforced concrete structures.

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